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RESEARCH ARTICLE

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The kinematics of eating with a spoon: bringing the food to the mouth, or the mouth to the food?

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Abstract In traditional reach-to-point and reach-to-grasp studies an increase in accuracy demands typically results in a lengthening of the deceleration phase of the reach and a freezing of the more distal joints. The purpose of the present experiment was to examine whether similar changes in the reach kinematics could be observed during a tool-using skill, as would be predicted from an effector independence perspective. Five subjects were required to eat two substances (i.e. a solid and a liquid one) that imposed different requirements on the accuracy of the movement. The subjects transported the substances from the plate into the mouth. A prolonged movement duration was found for the liquid as compared to the solid substance. However, rather than being exclusively due to a lengthening of deceleration phase, the larger movement duration resulted from a slowing down of the whole movement. Therefore, the skewed velocity profiles found in the traditional reach-to-grasp studies may well be the result of the accuracy demands only impinging on the final part of the movement trajectory, rather than being a consequence of central, effector-independent, organising principles. In addition, under increased accuracy demands subjects were shown to redistribute their movement in a proximodistal direction. Movements of the distal components were reduced to a minimum and the involvement of trunk and head movement increased.

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Introduction

Whereas in daily life grasping usually serves to displace an object from one location to another, researchers of human movement have focussed their attention almost exclusively on tasks in which subjects are required to pick up objects without any particular purpose. Consequently, prehension studies have sought an understanding of the coordination and control of reaching and grasping patterns by examining the effects of various manipulations and perturbations of the object to be grasped. Frequently used manipulations in this respect are object size (e.g. Jeannerod 1984; Paulignan et al. 1991a; Marteniuk et al. 1990; Bootsma et al. 1994), object location (e.g. Paulignan et al. 1991b), object fragility (Marteniuk et al. 1987; Savelsbergh et al. 1996) or task instructions (e.g. Marteniuk et al. 1987; Fisk and Goodale 1989). A recurring and consistent finding in these studies is that increased accuracy demands (e.g. grasping a smaller or more fragile object) lead to a prolonged duration of the reach movement, principally due to a (relative) lengthening of the deceleration phase. This lengthening of the deceleration phase runs parallel with a decrease in peak velocity and an increase in maximal grip aperture. For arm movements without grasping, such as aiming or pointing at targets or placing objects in holes, similar effects have been observed. There is ample evidence to suggest that more stringent spatial accuracy requirements (e.g. smaller target size, time constraints) are concurrent with an increase in the (relative) length of the deceleration phase and, simultaneously, a decrease in the magnitude of the peak velocity in pointing tasks (e.g. Adam 1992; Carlton 1994; MacKenzie et al. 1987; Milner and Ijaz 1990; Soechting 1984).

Pointing or reaching to grasp can be considered to be a whole body act involving not only the hand, but also the elbow, shoulder, trunk and head (cf. Soechting 1984). As an illustration, it has been shown that an increase in accuracy demands (e.g. grasping and transporting a full cup in comparison to an empty cup) is contiguous with an increase in trunk movement, and a decrease in angular motion of the elbow and shoulder joint (Steenbergen et al. 1995). In other words, when accuracy demands of the task are higher, subjects ‘freeze’ part of their movement system and increase the involvement of the trunk towards movement accomplishment (Steenbergen et al. 1995; see also Kaminski et al. 1995).

Thus, an appreciable amount of knowledge exists on the control of pointing and reach-to-grasp movements. In contrast, there is still a dearth of studies that examine the manner in which humans actually coordinate their movements during the displacement of objects such as during tool use. An exception is the work of Hollerbach (Atkeson and Hollerbach 1985; Hollerbach 1990), who examined the kinematics of vertical arm movements between two targets with hand-held loads (0–4 lb.). The loads only affected the tangential velocity of the hand (cf. Lacquanti et al. 1982). Typically, the studies dealt with unrestrained movements. Neither accuracy requirements nor movement objectives were taken into account, which makes generalisation to tool use hazardous. The present study, therefore, will focus on a tool-using skill: transporting different types of food to the mouth through the use of a spoon.

A portion of the studies on tool use touch upon the developmental aspects of this skill (e.g. Connolly and Dalgleish 1989; Steenbergen et al. 1997). Development in the use of hand-held spoons is characterised by a transition from power grip to precision handling, and by a decrease in the amount of different grips adopted (e.g. Connolly and Dalgleish 1989). Recently, attention has also been directed to adult hand-mouth coordination in eating tasks (Castiello 1997; Mathiowetz and Wade 1995).

Castiello (1997), for instance, had subjects eat different-sized pieces of cheese. The arm movement of bringing the cheese to the mouth and the pattern of mouth aperture were examined, with the latter being a reflection of the grasp component. In agreement with the ‘traditional’ reach-to-grasp studies, a lengthened deceleration phase of the hand was found for the smallest pieces of cheese as well as an increased mouth aperture with an increase in food size (cf. Bermejo et al. 1989; Bermejo and Zeigler 1989). These findings suggest that similar coordination principles may apply for both the coordination of reaching and grasping, and hand-mouth coordination; hence, that coordination is independent of the body part(s) involved. Similar parallelisms have been demonstrated in the context of handwriting (e.g. Bernstein 1967). That is, the topology of the movement appeared similar regardless of the way it is produced (e.g. using the hands, mouth or feet). Although Wright (1990), in a thorough analysis of right- and left-handed writing, casts serious doubts on its existence, this effector independence is proposed to reflect abstract levels of motor programming and/or comprising similar neural structures (e.g. Bernstein 1967; Castiello 1997; Hoff and Arbib 1993; Tresilian and Stelmach 1997).

The present study is designed to evaluate the effector independence proposition for the tool-using skill of eating. Tool use implies a change in the dynamics of the effector system (cf. Steenbergen et al. 1997). However, if coordination is effector independent, it would be hypothesised that the effect of increased accuracy demands on, for instance, the transport of food with a spoon from a plate to the mouth affects the reach kinematics similarly as in the standard pointing and reach-to-grasp studies. To test this hypothesis, we had subjects use a spoon to eat substances that impose different accuracy demands. A solid substance (kale) and a liquid substance (water or lemonade) were used, under the assumption that the accuracy demands for transporting a liquid substance are larger. It is expected that the deceleration phase of the reach is relatively longer in the case of transporting water.

Following Steenbergen et al. (1995), it was further examined whether the movements of the individual joints are restricted or frozen with increasing accuracy demands, by calculating the amount of angular motion of the individual arm joints. A smaller amount of angular motion is expected when water is transported. Also, the involvement of the trunk and head were examined. When the accuracy demands increase (i.e. when it is more difficult not to spill), the trunk and head involvement are expected to increase in order to shorten the distance the hand has to cover. Henceforth, simultaneously with the increased trunk and head movement, a decreased involvement of the arm segments is expected.

In sum, in the present study the effect of accuracy demands on the coordination during eating is examined. Subjects had to eat kale and water with a spoon. First, we examined whether the accuracy demands have similar effects on the reach kinematics as was previously found for ‘plain’ aiming and prehension tasks, which may point to an ‘effector free’, independent, coordination principle. Second, the contribution of the different segments towards the accomplishment of the task was examined under the assumption that an increase in accuracy demands leads to ‘freezing’ of the more distal joints and an enlarged trunk and head involvement.

Materials and methods

Participants

Three male and two female university students, ranging in age from 23 to 31 years, volunteered as subjects in the study. All were naive as to the purpose of the experiment.

Experimental design and procedure

The participant was comfortably seated at a table where, in front of him/her, a soup plate filled with either kale or water was placed. Kale, a traditional Dutch dish containing mashed potatoes and green cabbage, served as the solid substance and water or lemonade as the liquid substance. As the risk of spilling is larger for a liquid, transporting water was assumed to impose larger accuracy demands. Each subject was required to eat 20 spoons filled with

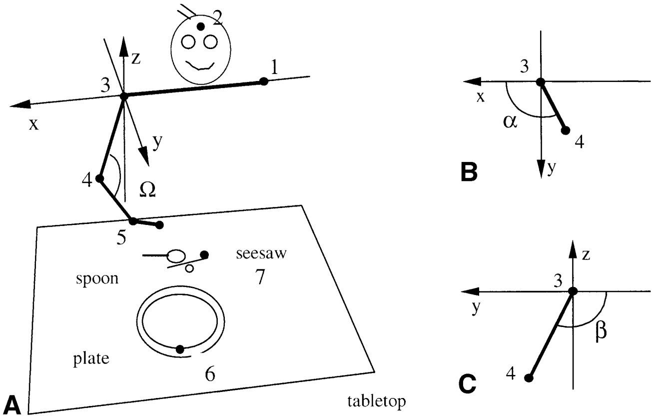

Fig. 1 The experimental set-up **(a)**. Shown are the locations of the markers: *1* contralateral shoulder, *2* head, *3* ipsilateral shoulder, *4* elbow, *5* wrist, and *6* plate. Angle Ω represents elbow flexion **(a)**, angle α represents shoulder flexion **(b)**, and angle β represents shoulder elevation **(c)**

kale followed by 20 spoons filled with water or lemonade. Prior to each trial the subject placed the right hand on the table-top. The spoon was located in between the soup plate and the seated subject (see Fig. 1a). The total task encompassed grasping the spoon and (1) reaching with the spoon to the plate, (2) filling the spoon with the substance, and (3) transporting the filled spoon to the mouth and emptying it. Aside from instructing subjects 'to eat as you would normally do', no additional constraints were imposed upon them. The experiment took approximately 30 min to complete.

Data analysis and dependent variables

A three-dimensional semiautomatic video-based motion registration system (VICON, Oxford Metrics Ltd.) recorded the position of six light-reflecting markers (diameter 25 mm), with four cameras, at a sample rate of 60 Hz. Calibration errors were less than 3 mm and calibration space measured 80 cm by 80 cm by 120 cm. Five markers were attached to the subject's body: the wrist, the elbow, the ipsilateral and contralateral shoulder and the forehead (just above the nose). Two other markers were used, one attached to the soup plate (Fig. 1a), and one to the end of a small seesaw on which the spoon was placed before each trial. The positional data were filtered using a second-order Butterworth filter with a cut-off frequency of 7 Hz, which was applied twice in order to negate phase shift.

The present study reports data from the third phase, which will be denoted 'reach-to-mouth phase'. Only the total duration of the reach-to-plate and fill phase will be reported, because it was established afterwards that for a large amount of trials it was difficult to reliably distinguish the end of the reach-to-plate phase from the start of the fill phase. This was partly due to the different movement solutions or 'eating styles' used, not only across, but also within, subjects, as revealed by observations from VHS video recordings. For instance, the spoon was entered into the plate from different directions, most frequently from the side, but also from the back and the front of the plate. In addition, different grip patterns were used, predominantly the adult grip (i.e. the spoon held between the thumb and index finger), but also the power grip (i.e. a fist grip that involves all fingers with the opposing thumb on the spoon; cf. Connolly and Dalgleish 1989). The latter type requires many more arm movements to fill the spoon, while in the case of an adult grip a wrist rotation will suffice. Also, during the experiment the subjects were emptying the plate, which led to an increasing amount of (re)fill or stir movements, especially in the case of kale. Such (re)fill movements may have determined the grip type as well as the direction in which the plate was entered. In the case of water, the filling movements were often less distinct, and the reach-to-plate phase and fill phase merged into one.

The moment of initiation of the reach-to-plate phase (MIRP) was defined by the moment the small seesaw started to move in the *z*-direction (see Fig. 1 for a definition of the coordinate axis). MIRP was determined by first calculating the velocity profile in the *z*-direction of the seesaw marker, and subsequently determining the moment at which the velocity profile crossed the zero-axis for the last time before it started to increase continuously. The moment of initiation of the reach-to-mouth phase (MIRM) was defined by the moment at which the spoon left the plate. MIRM was determined by first calculating the distance between the plate and wrist marker, calculating its velocity profile, and finally determining the moment at which the velocity profile crossed the zero-axis for the last time before it started to increase continuously. The moment of completion of the reach-to-mouth phase (MCRM) was defined by the moment the spoon entered the mouth. MCRM was determined by first calculating the distance between the forehead and wrist marker, and subsequently determining the moment the distance reached a local minimum (i.e. when its velocity profile reached zero). The moment of peak velocity of the reach-to-mouth phase (MPVRM) was defined as the moment between MIRM and MCRM at which the tangential velocity of the wrist marker was at its maximum.

These kinematic landmarks were used to define the dependent variables. For the reach-to-plate and fill phase, (a) the total movement time (i.e. MIRM-MIRP) was calculated. For the reach-to-mouth phase (b) the movement time (i.e. MCRM-MIRM), (c) the time to peak velocity (i.e. MPVRM-MIRM), (d) the time spent decelerating (MCRM-MPVRM), (e) the percentage of time to peak velocity (i.e. the time to peak velocity divided by the movement time and multiplied by 100), and (f) peak velocity were computed.

In addition, the total number of zero-crossings in the acceleration profile of the reach-to-mouth phase, which is equivalent to inflections in the velocity profile, was calculated as a measure of irregularity of the movement. Also, the total distance covered by the wrist, ipsilateral shoulder, and the head were calculated from the tangential position profiles of the matching markers.

Three joint angles were defined, shoulder flexion, shoulder elevation and elbow flexion. The elbow angle was constructed by linking the wrist marker and the elbow marker and the elbow and the shoulder marker to line segments. Subsequently, the angle between them was calculated. Shoulder flexion was defined in the *XY*-plane and shoulder elevation was defined in the *YZ*-plane (see Fig. 1b,c). To assess the contribution of the joints to movement completion, and the level to which 'freezing' was instigated, the amount of angular change during the movement was calculated for each joint separately.

When one of the dependent variables could not be defined (i.e. a marker was out of view, mainly as a consequence of rotation movements, or, in rare occasions because MIRM could not be determined), the trial was excluded from further analysis. As a result, the number of trials analysed was dissimilar among subjects. Twelve kale and water comparisons were made for subject 4, 13 comparisons for subjects 1 and 5, and 16 comparisons for subjects 2 and 3. To examine the differences for Substance and Subject, the separate scores of each dependent measure were submitted to a 5(Subject) by 2(Substance) analysis of variance (ANOVA) with repeated measures on the last factor. Post hoc comparisons were performed using Newman-Keuls routines ($P<0.05$). The factor Subject was included because it could not be ruled out a priori that the different movement solutions or 'eating styles' would result in distinct kinematic patterns for different subjects.

Results

Reach-to-plate and fill phase: kinematics

The total movement times for the reach-to-plate and fill phase are shown in Table 1 for each subject. Except for

Table 1 Total movement times (ms) for the reach-to-plate and fill phase. Standard deviations are in parentheses

Subject	Kale	Water	Total
1	1387 (244)	1561 (270)	1485 (269)
2	1300 (264)	1027 (115)	1159 (242)
3	1105 (162)	1146 (114)	1126 (139)
4	2503 (612)	1248 (323)	1767 (776)
5	2097 (419)	1992 (448)	2033 (434)
Total	1629 (632)	1415 (459)	

Table 2 Overview of the kinematic characteristics of the wrist for the reach-to-mouth phase. Standard deviations are in parentheses

Subject	Kale	Water	Total
Movement time (ms)			
1	1217 (353)	1201 (300)	1209 (321)
2	718 (117)	832 (208)	776 (176)
3	916 (168)	1239 (179)	1077 (237)
4	1122 (252)	1419 (236)	1271 (283)
5	997 (274)	1305 (192)	1151 (280)
Total	977 (291)	1182 (299)	
Time to peak velocity (ms)			
1	722 (252)	782 (166)	752 (212)
2	358 (98)	411 (200)	385 (157)
3	488 (111)	613 (231)	550 (189)
4	442 (165)	669 (177)	556 (204)
5	509 (173)	676 (288)	592 (248)
Total	498 (200)	620 (246)	
Time spent in the deceleration phase (ms)			
1	495 (152)	419 (213)	457 (185)
2	361 (104)	421 (142)	391 (126)
3	428 (89)	626 (179)	527 (172)
4	681 (133)	750 (182)	715 (160)
5	488 (174)	629 (212)	559 (203)
Total	480 (165)	563 (221)	
Percentage of time to peak velocity			
1	59.0 (7.8)	66.9 (12.9)	63.0 (11.2)
2	49.9 (12.6)	49.5 (16.9)	49.7 (14.7)
3	53.1 (6.0)	48.9 (13.6)	51.0 (10.5)
4	38.8 (7.8)	47.4 (9.7)	43.1 (9.7)
5	51.8 (14.8)	51.0 (17.4)	51.4 (15.8)
Total	50.8 (11.8)	52.5 (15.8)	
Peak velocity (mm/s)			
1	580 (172)	340 (73)	460 (178)
2	457 (97)	314 (46)	386 (104)
3	489 (67)	344 (33)	416 (90)
4	469 (47)	282 (55)	375 (108)
5	539 (63)	329 (58)	434 (123)
Total	505 (106)	323 (56)	

subject 4, who appeared to need a long time to fill the spoon, no large differences between the solid and liquid substance were found.

Reach-to-mouth phase: kinematics

Table 2 displays the kinematic characteristics of the wrist movement during the reach-to-mouth phase. In accordance with the predictions, based on the accuracy demands imposed by the two substances, a significant main effect of Substance ($F_{(1,65)}$=24.69, P<0.001) was found for movement time. Also significant effects of Subject ($F_{(4,65)}$=22.50, P<0.001) and Subject by Substance were found ($F_{(4,65)}$=2.62, P<0.05).

Post hoc analysis revealed that four subjects needed a longer time to transport the water in comparison to kale. For subject 1, however, the difference in movement time between both substances was small (16 ms) and not significant.

Figure 2 shows representative tangential velocity profiles of subjects 4 (Fig. 2A,B) and 5 (Fig. 2C,D). Comparison of these profiles for the kale and the water conditions revealed a lengthening of both the times spent before and after peak velocity and a simultaneous decrease of peak velocity for the water condition. In addition, the velocity profiles for water show an increase in the irregularity of the reach-to-mouth phase, indicating that the decrease in peak tangential velocity runs parallel with an increase in the number of submovements.

Time to reach peak velocity was significantly enlarged for water ($F_{(1,65)}$=14.45, P<0.001) compared to kale. A significant main effect of Subject ($F_{(4,65)}$=13.72, P<0.001) was found for the time to peak velocity as well. Post hoc analysis showed that the latter effect could be attributed to a longer time to peak velocity for subject 1 as compared to the other subjects (Table 2).

For the time spent in deceleration, significant main effects of Substance ($F_{(1,65)}$=9.35, P<0.0l), Subject ($F_{(4,65)}$=13.81, P<0.001), as well as a significant interaction between Subject and Substance ($F_{(4,65)}$=3.27, P<0.05) were found. Post hoc analysis indicated that for four subjects the deceleration phase was extended in the case of water (Table 2). For subject 1 this effect was reversed; the duration of the deceleration phase was larger for the kale as compared to the water.

In contrast, examination of the percentage of time to peak velocity showed the main effect of Substance to disappear (Table 2). That is, for both substances a similar percentage of time was needed to reach peak velocity, or conversely was spent decelerating relative to total movement duration. Subject 1 took a larger proportion of the movement time to reach peak velocity in comparison with the other four subjects ($F_{(4,65)}$=6.97, P<0.001).

The absolute peak velocity was shown to decrease when water was transported ($F_{(1,65)}$=169.73, P<0.001) compared to kale (Table 2). Also, a significant main effect of Subject was revealed for peak velocity ($F_{(4,65)}$=5.64, P<0.001). Again, this effect was due to subject 1, who displayed a larger peak wrist velocity.

Finally, with respect to the number of zero-crossings in the acceleration profile significant effects were found for Substance ($F_{(1,65)}$=99.42, P<0.001), Subject ($F_{(4,65)}$=5.91, P<0.001), and for the interaction of Substance and Subject ($F_{(4,65)}$=6.04, P<0.001). Post hoc tests revealed that, with exception of subject 1, the number of zero-crossings was larger for water than for kale (Table 3).

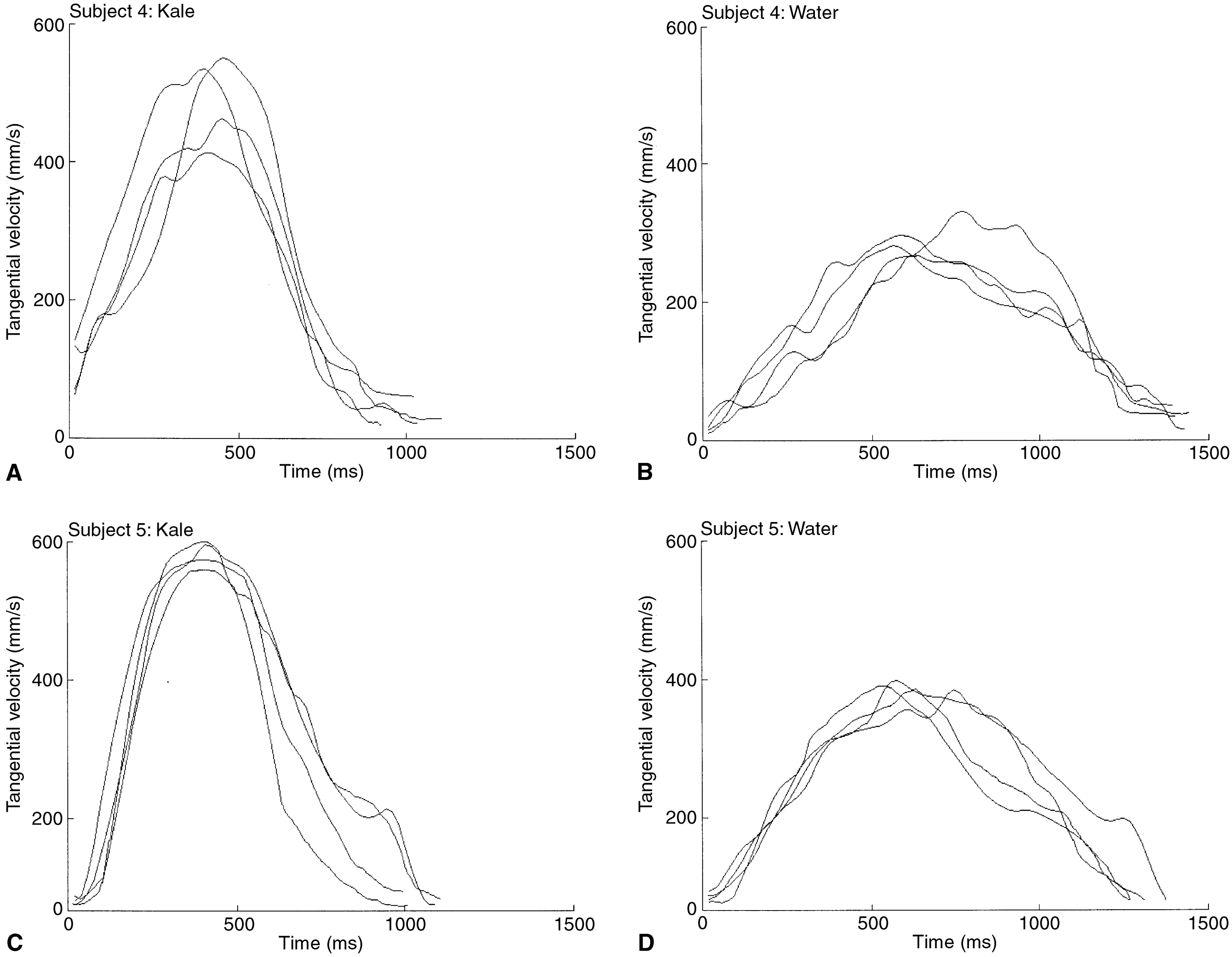

Fig. 2A–D Representative tangential velocity profiles of the reach-to-mouth phase. **A** represents the tangential velocity profile for subject 4 eating kale, **B** represents subject 4 eating water, **C** represents subject 5 eating kale, and **D** represents subject 5 eating water

Table 3 The number of zero-crossings of the acceleration profile for the reach-to-plate and fill phase. Standard deviations are in parentheses

Subject	Kale	Water	Total
1	7.9 (3.5)	8.5 (3.3)	8.1 (3.1)
2	3.1 (1.8)	9.8 (3.7)	6.4 (4.4)
3	7.3 (2.3)	11.0 (3.1)	9.2 (3.3)
4	7.2 (2.2)	12.5 (3.3)	9.8 (3.9)
5	3.8 (2.2)	10.1 (3.0)	7.0 (4.1)
Total	5.8 (3.1)	10.4 (3.4)	

Reach-to-mouth phase: joint involvement

With respect to ‘freezing’ of the elbow and shoulder joints, the amount of angular change was considered. The results of this calculation are displayed in Table 4. For the amount of elbow flexion, significant main effects of Substance ($F_{(1,65)}$=13.95, P<0.001) and Subject ($F_{(4,65)}$=5.41, P<0.001) were found. Post hoc analysis of the Subject by Substance interaction ($F_{(4,65)}$=3.95, P<0.001) indicated that in subjects 1, 2, 4, and 5 the amount of elbow flexion decreased during the transport of water, whereas this effect was reversed for subject 3.

Similar main effects of Substance ($F_{(1,65)}$=7.74, P<0.01) and Subject ($F_{(4,65)}$=13.19, P<0.001) were also discerned for the amount of shoulder elevation. Post hoc analysis of the significant Subject by Substance interaction ($F_{(4,65)}$=2.96, P<0.05) revealed that the effects on shoulder elevation were opposite to those on elbow flexion. That is, for four subjects (subjects 1, 2, 3, 5) the amount of shoulder elevation increased when water was transported, while this effect was reversed for the other subject (subject 4).

Finally, for the amount of shoulder flexion, only a main effect of Subject was found ($F_{(4,65)}$=5.22, P<0.01). Post hoc analysis showed that the amount of shoulder flexion was largest for subject 5.

Reach-to-mouth phase: distances covered

To assess the contribution of the different movement components towards completion of the movement goal,

Table 4 Range of angular movement in the three joints, that is, elbow extension, shoulder flexion and shoulder elevation. Standard deviations are in parentheses. All measures are in degrees

Subject	Kale	Water	Total
Elbow			
1	35.1 (12.3)	29.1 (5.8)	32.1 (9.9)
2	43.7 (16.5)	21.3 (13.3)	32.5 (18.6)
3	29.7 (4.5)	33.0 (7.4)	31.3 (6.3)
4	34.8 (12.6)	29.0 (7.8)	31.9 (10.7)
5	50.6 (23.3)	38.8 (16.2)	44.7 (20.6)
Total	38.6 (16.3)	29.9 (12.1)	
Shoulder flexion			
1	5.5 (3.5)	10.9 (3.9)	8.2 (4.5)
2	18.1 (17.3)	8.5 (13.4)	13.3 (16.0)
3	5.4 (3.5)	10.5 (10.1)	7.9 (7.9)
4	19.1 (9.2)	15.9 (15.3)	17.5 (12.5)
5	19.3 (16.3)	25.1 (33.1)	22.2 (25.7)
Total	13.2 (13.2)	13.7 (18.1)	
Shoulder elevation			
1	5.5 (4.1)	10.1 (5.1)	7.8 (5.1)
2	9.6 (6.3)	10.8 (6.6)	10.2 (6.4)
3	5.3 (3.2)	9.9 (5.7)	7.6 (5.1)
4	18.9 (9.6)	15.8 (14.6)	17.4 (12.2)
5	13.7 (11.9)	25.2 (7.5)	19.5 (11.4)
Total	10.2 (8.9)	14.0 (9.9)	

Table 5 Overview of the overall distances (mm) covered by the wrist, shoulder and head. Standard deviations are in parentheses

Subject	Kale	Water	Total
Wrist			
1	268 (78)	215 (53)	242 (71)
2	276 (67)	429 (159)	358 (137)
3	179 (26)	194 (31)	187 (30)
4	250 (30)	207 (14)	229 (32)
5	270 (59)	254 (28)	262 (47)
Total	247 (64)	258 (115)	
Shoulder			
1	38 (10)	42 (34)	40 (25)
2	203 (189)	277 (296)	241 (247)
3	58 (21)	189 (213)	124 (163)
4	322 (336)	581 (481)	452 (428)
5	243 (279)	375 (376)	309 (332)
Total	169 (227)	288 (350)	
Head			
1	107 (45)	85 (35)	97 (42)
2	107 (31)	136 (17)	122 (29)
3	105 (26)	149 (40)	128 (40)
4	114 (23)	115 (22)	115 (22)
5	66 (33)	93 (15)	80 (29)
Total	101 (36)	118 (37)	

the overall distances travelled by the wrist, shoulder and head were calculated. Table 5 displays the results of this calculation. For the distance covered by the wrist, a significant main effect of Subject ($F_{(4,65)}$=23.13, P<0.001) and a Subject by Substance interaction ($F_{(4,65)}$=5.92, P<0.001) were present. Post hoc comparisons revealed that for three subjects the distance covered by the wrist decreased for water (subjects 1, 4, and 5), for subject 3 the difference in distance was not significant, and for subject 2 the wrist covered a larger distance for water compared to kale (Table 5).

With respect to head movement, main effects for Substance ($F_{(1,65)}$=5.38, P<0.0l) and Subject ($F_{(4,65)}$=11.07, P<0.001) were found. Post hoc analysis of the significant Subject by Substance interaction ($F_{(4,65)}$=5.38, P<0.001) revealed that for three subjects 2, 3, and 5 the distance covered by the head was larger when water was transported. For subject 4 a slightly larger distance was covered by the head during transport of water, but this was not significant. Subject 1 covered a smaller distance with the head during the transport of water.

Finally, for the shoulder displacement, main effects for Substance ($F_{(1,65)}$=8.42, P<0.0l) and Subject ($F_{(4,65)}$=7.69, P<0.001) were revealed. A larger shoulder displacement was evident during the transport of water compared to kale (Table 5). However, the absolute amount of shoulder displacement was unevenly distributed among subjects.

Discussion

Kinematic characteristics

The purpose of the present experiment was to examine the kinematics of an eating action under different accuracy constraints imposed. Subjects were required to use a spoon for eating kale and water, with the latter imposing higher accuracy constraints, because of an enlarged risk of spillage. Specifically, we sought to find out whether the invariances in movement organisation observed in the standard reach-to-point and grasp studies also applied for reaching with a tool. Handling a tool changes the dynamics of the effector, not unlike adding an extra joint. Consequently, control is primarily directed at the interface between tool and environment instead of between hand and object (Steenbergen et al. 1997). Hence, if the kinematics of eating with a spoon show similar characteristics to those observed in reaching to point or grasp, this would be an indication of the use of a common coordinating schema independent of the effector involved (cf. Bernstein 1967; Castielllo 1997; Tresilian and Stelmach 1997).

Generally, the standard reach-to-point and reach-to-grasp studies have shown that an increase in the accuracy demands of the task, for instance by using smaller objects (e.g. Marteniuk et al. 1990; Soechting 1984), more fragile objects (e.g. Savelsbergh et al. 1996), or by inducing a change in the task dimensions (reaching a full versus an empty cup; Steenbergen et al. 1995: throwing an object or placing it in a tight-fitting well; Marteniuk et al. 1987; placing pegs in holes with different diameters; Milner and Ijaz 1990), results in an extended movement duration. Moreover, this lengthening of the movement duration could almost always be attributed to a lengthening of the low-velocity phase (i.e. the deceleration phase).

In line with these studies, we found a significant lengthening of movement duration when water was transported in comparison to kale for four of the five subjects. Nonetheless, it was shown that this lengthening was not exclusively brought about by a lengthening of the deceleration phase, but rather a slowing down of the whole movement. Relative to total movement duration the length of the deceleration phase did not differ across the movement conditions. Thus, the idea of an effector-independent organisation principle could not be confirmed for the present task (cf. Wright 1990). Rather, it would appear that it is the distribution of the accuracy constraints that determines the shape of the velocity profile. This contention is consistent with a mathematical model proposed by Milner (1992; Milner and Ijaz 1990), which aims to explain the generation of movements requiring endpoint precision. The basic idea is that the tangential velocity profile of a movement reflects the superimposition of submovements, each of which is a scaled (in magnitude or duration) version of a prototype velocity profile. The number of submovements increases, either due to increasing accuracy requirements, or to a slowing down of the movement. In the case of movements demanding accuracy, the submovements are thought to represent corrective actions that may be taken throughout the course of the movement. Two predictions follow from Milner's model. First, when accuracy constraints become more stringent the irregularity of the velocity profile would increase, and, second, higher accuracy demands would enlarge movement duration. The first prediction appears to be supported by the increased number of zero-crossings in the case of transporting water, which suggest that the movement became less fluent (i.e. consists of more submovements). Also, the second prediction seems confirmed. Wherever accuracy demands are imposed, the duration of the (sub-)movement is lengthened. Thus, when transporting food to the mouth with a spoon, accuracy demands impose themselves throughout the movement. Subjects solve this movement problem by slowing down the complete movement and at the same time retaining the (more or less) symmetrical velocity profile. Similarly, for unrestrained arm movements the accuracy demands are evenly distributed throughout the movement. Perturbing such arm movements by having subjects move with different hand-held loads leads to a simple velocity scaling (e.g. Atkeson and Hollerbach 1985) as predicted by Milner's model. Typically, in studies where subjects had to reach to point (e.g. Soechting 1984), reach to grasp (e.g. Marteniuk et al. 1990), reach to bring food to the mouth by hand (Castiello 1997), or bimanually reach for objects (Tresilian and Stelmach 1997), the accuracy constraints impose themselves only in the latter part of the movement, which resulted in a prolonged deceleration phase. The assumption that the time to peak velocity is initially (pre-)programmed and the deceleration phase is visually modulated to correct for errors (e.g. Bermejo et al. 1989; Bootsma and Van Wieringen 1992) may, therefore, partly be an "artefact" of the tasks used. In sum, based on the present findings and Milner's model, it might be suggested that the level of asymmetry of the velocity profiles of arm movements is a direct reflection of the distribution of the imposed accuracy demands.

A final remark on the individual differences, or different 'eating styles', is that if we assume that the observed kinematics are to a large extent determined by the imposed accuracy constraints, rather than being the result of an abstract effector-independent motor scheme, then the individual differences may be regarded as a reflection of different solutions to the movement problem. In the present experiment, for instance, subject 1 did show an increase in percentage of time to peak velocity when transporting water. Tentatively, this might suggest that for the eating style used by subject 1 the accuracy demands were unequally distributed in the reach-to-mouth phase. Why this is the case remains unclear. However, it does underline the importance of considering each subject separately whenever the instructions leave the task relatively unconstrained.

Movement reorganisation

The second issue raised in the present study was how the movement system solves the movement problem at hand. As seen in the previous section, the total movement is slowed down to enhance control over the spoon transport in the case of water. However, the present results also showed a redistribution of segments involved. Basically, subjects increased head movement to get the spoon in the mouth in the case of water. This allows for a decreased movement of the end-effector, in this case the hand-with-spoon, thereby promoting movement control. Specifically, subjects decreased the amount of elbow flexion and increased the amount of shoulder elevation when the water was transported compared to kale. For three of the five subjects a significant increase in head movement was also found in these instances. These subjects 'freeze' the more distal movement components of the arm and bring the water to the mouth basically by an elevation of the shoulder and an increasing involvement of the head movement. Hence, the mouth is brought to the spoon in these instances. This result points to the freezing of degrees of freedom as a general principle underlying movement (re-)organisation and lend support to a proximodistal direction in movement organisation (for similar results, see Steenbergen et al. 1995, 1999; Vereijken et al. 1992; Van Emmerik and Newell 1990; Gesell 1946).

Hence, the findings indicate that subjects limited the excursion of the more distal movement components (i.e. elbow flexion and wrist displacement decreased) and enlarged the contribution of the more proximal components (i.e. shoulder elevation as well as shoulder and head displacement increased) towards movement completion under more strenuous accuracy conditions. These combined findings raise the issue as to how these distal and proximal components are coordinated when transporting food to the mouth. In this respect, Lee (1976 1998; Lee et al. 1991, 1992, 1993: see also Bardy and Warren 1997; Yilmaz and Warren 1995; Zaal and Bootsma 1995) argued that in (non-)collision tasks, such as drivers braking for an obstacle, or birds docking on a feeder, it is the closure of the gap between the actor and the target that is directly controlled. In addition, Lee suggested that such control is based upon information about the time-to-closure of the gap. It can be shown mathematically that the time-to-closure of the gap is optically specified by the relative rate of expansion of the approached target in combination with the relative rate of constriction of the gap between the actor and the target (Lee 1976; Bootsma and Oudejans 1993). This optical information was denoted tau. Lee argued that by keeping the rate of change of tau constant the closure of the gap is controlled. Moreover, the value at which the rate of change of tau is kept constant defines the type of collision (i.e. hard vs soft collisions). It might be argued that for the present task, rather than being controlled independently, the hand and head movements are controlled as one ensemble. Hence, regardless of whether the spoon is brought to the mouth (as appears to be the case for solid substances) or whether the mouth is brought to the spoon (in the case of liquid substances), it may be the time-to-closure of the gap between the spoon and the mouth that is regulated.[1] One way to address this issue experimentally is to perturb either the hand or head movement. Compensatory movements in the unperturbed component would be an indication that the hand and head are regulated as an ensemble.

In sum, the present study shows that if accuracy demands affect the complete movement trajectory a symmetrical velocity profile is found. The skewed velocity profiles found in the traditional reach-to-point and reach-to-grasp studies may therefore well be the result of the accuracy demands only impinging on the final part of the movement trajectory, rather than being a consequence of central organising principles.

In addition, under the increased accuracy demands subjects were shown to redistribute their movement in a proximodistal direction. Movements of the distal components are reduced to a minimum and the involvement of trunk and head movement increased.

[1] Analysis (for the method employed, see Lee et al. 1991) of the deceleration phase of the reach-to-mouth movement showed for both substances substantial linear regressions (water on average 0.89 and kale 0.92) with a regulation based on the time-to-close the gap by keeping the rate of change of tau constant. The value at which tau was kept constant was slightly higher for water (on average 0.50) than for kale (0.44), suggesting a soft collision (Lee 1976). However, before drawing any firm conclusions, alternative strategies need to be formulated (for an attempt see Zaal and Bootsma 1995) so that a direct comparison between possible strategies can be made

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